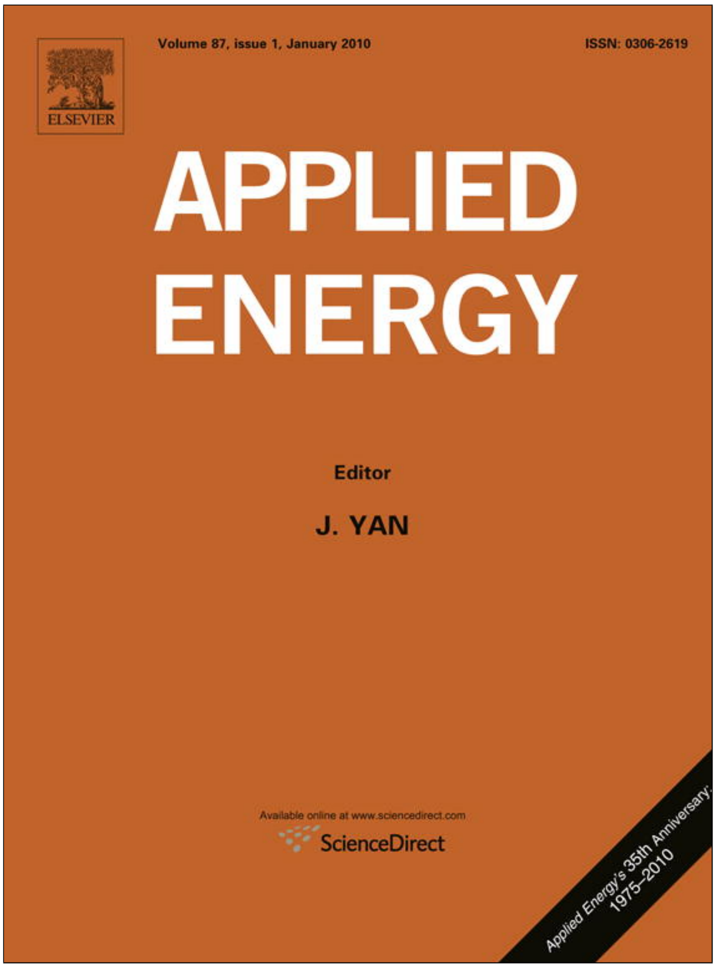
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Characteristics of co-combustion and kinetic study on hydrothermally treated municipal solid waste with different rank coals: A thermogravimetric analysis

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ABSTRACT

This study presents an investigation on the influence of hydrothermally treated municipal solid waste (MSW) on the co-combustion characteristics with different rank coals, i.e. Indian, Indonesian and Australian coals. MSW blends of 10%, 20%, 30% and 50% (wt.%) with different rank coals were tested in a thermogravimetric analyser (TGA) in the temperature range from ambient to 700 °C under the heating rate of 10 °C/min. Combustion characteristics such as volatile release, ignition and burnout were studied for the blend fuel. Different ignition behavior was observed depending on the blends composition and the coal rank. The result of this work indicates that the blending of MSW improves devolatization properties of coal. But it was found that the co-combustion characteristics of MSW and coal blend cannot be predicted only from the pyrolytic and or devolatization phenomena as the other factors such as the coal quality also plays a vital role in deciding the blends co-combustion characteristics. The TGA combustion profiles showed that the combustion characteristics of blends followed those of parent fuels in both an additive and non-additive manners. These experimental results help to understand and predict the behavior of coal and MSW blends in practical applications.

1. Introduction

In recent years there has been an increase in problem faced for disposal of municipal solid waste (MSW) in developing countries like India and in developed countries as well. The present practice of MSW disposal in open dumps and landfills is creating environmental pollutions. The traditional method of disposing MSW by incineration is facing with the problems of its pollution as well as the public opposition and thus not preferred globally. Thermal disposal methods like combustion, pyrolysis and gasification offer great benefits over traditional methods of disposing MSW. These thermal methods not only recover useful energy values from MSW but also reduce the quantity of waste being ultimately sent to landfill. On the other hand, co-utilization of biomass with coal in recent years has proved to be an effective utilization option for reducing greenhouse gas emissions and has opened an era for utilizing wastes like sewage sludge, waste tyre, etc., with coal. The waste derived fuels can be very well used in many applications and replace some part of fossil fuels, which is becoming scarce and depleting at a faster rate.

Hence replacing some part of coal by waste derived fuels can reduce emission. Blending of waste derived fuel with coal is an immediate choice on account of various factors such as reduction in pollution, effective management and utilization of waste and quicker implementation in the existing facility. In spite of many advantages, there are problems associated with the use of waste derived fuels with coal. In general, the firing equipment like boiler furnaces and cement kilns are designed for a particular fuel. For co-combustion of these waste derived fuels with coal, the firing equipment needs to be designed for a predetermined blending ratio. Even if the equipment is designed for firing a particular blend fuel, the performance will highly depend on the homogeneity of the blending [1]. Further a large difference in their energy levels poses another problem in their usage. The main problems associated with the use of MSW are their moisture content and variety of compositions, unlike other regular biomass. These technical barriers need to be overcome in order to accelerate the use of MSW co-combustion technology for promoting the clean, efficient use of MSW.

In India, coal is imported mainly from Indonesia to fill the gap between demand and supply that power utilities are currently facing with. Indonesian coal has lower ash content and higher calorific value compared with Indian coal [2]. As the numbers of coastal plants are increasing in the 4000 MW ultra mega power project package, the Indian government is considering revising the policy of depending on imported coal [3]. Also the process industries like steel and cement companies are importing coal from Australia due to its higher quality and lower ash content. Many Indian energy

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companies have already started investment on Indonesian and Australian coal mines to ensure coal supplies to their utilities [4]. In general, Australia and Indonesia are the top ten coal producers in the world and also the leading two coal-exporting nations [5]. So in this study, Indian coal and imported coals mainly used in India like Indonesian and Australian coals were used to study the effect of MSW blending with coal on the ignition characteristics.

Many researchers in the field of co-combustion have studied coal with woody biomass, sewage sludge and waste tyre, paper, etc. [6–11]. Some studies on specific material such as plastic, cellulose and paper have been reported [12–16]. However, co-combustion of treated MSW with coal has not so much been studied yet. Most of the previous studies on MSW co-combustion are merely focused on fundamental analysis without an aim of practical implementation due to its complexity [12,15]. Further, very few authors carried out test on co-combustion of MSW and coal, but they have reported a very low efficiency predominately caused by the MSW moisture [17]. In addition to that, the general fear of early ignition of coal due to early volatile release by biomass fuel has not been clarified yet, which is the main cause of concern for many plant operators due to fire hazard. Many literatures in this field of co-combustion discussed the early ignition of blend due to early release of volatile from biomass or MSW based on the pyrolysis process alone [18–20]. Hence this study aims at evaluating the effect of MSW blending on ignition performance of coal by way of both pyrolysis and combustion phenomena.

The goal of this study is to utilize a novel pretreatment technology to treat MSW to make it suitable for blending with coal so as to reduce coal imports and to promote effective use of MSW. The objective of this paper is to find out how the early volatile release from MSW affects the ignition of coal and also to investigate on the extent that this phenomenon is related to the coal properties.

2. Experimental

2.1. MSW sampling

In this study sorted MSW supplied from a local city in Hokkaido of Japan was employed for co-combustion with coals. The average MSW composition which excludes the food residue is given in Table 1.

2.2. Hydrothermal treatment

A schematic diagram of the demonstration plant used in this experiment was shown in Fig. 1, and the treatment parameters are given in Table 2. The demonstration plant primarily consists of a reactor, a boiler, a steam condenser and waste water treatment. The reactor is a pressure vessel of 3 m^3 in volume. In this batch type of treatment, sorted MSW of around 500–1000 kg was supplied into the reactor. Then saturated steam at the pressure of 2 MPa is supplied into the reactor gradually from a boiler. The uniformity of treatment throughout the MSW sample was ensured by a rotor, which rotated inside of the reactor at a constant speed of around 20 rpm. When the pressure and temperature in the reactor reached the target values, the reactor was held at this condition until the end of the holding time period. When the holding time finished, steam supply stopped and the pressure of the reactor was reduced by discharging the residual steam. The released steam was condensed and reused again for producing steam in the boiler, after water treatment. Once the reactor pressure fell down to atmospheric, the treated product from the reactor was extracted. Then the treated products were dried naturally in an open space for about 2 days to obtain dried products used for this experiment.

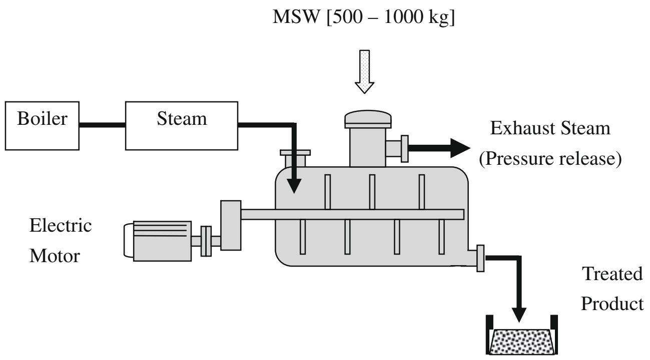

Fig. 1. Schematic diagram of the hydrothermal treatment process.

Table 2
Hydrothermal treatment of MSW.

Hydrothermal treatment parameters	
Steam pressure (MPa)	2.0
Heating-up time (min)	30
Holding time (min)	30
Pressure release time (min)	10

Table 1
Property of MSW.

	MSW	Treated MSW [d]
Moisture[a] (%)	33	11.6
Combustible[b] (%)	50	72.4
Ash[b] (%)	17	16
Density[c] (kg/m^3)	150	610
Calorific value		
HHV[c] (MJ/kg)	18.05	17.84

HHV-high heat value.
[a] As received basis.
[b] Wet basis.
[c] Dry basis.
[d] Hydrothermally treated MSW, dried naturally for 48 h.

Fig. 2 shows the MSW before and after the hydrothermal treatment. The properties of the hydrothermally treated MSW are compared with those of the untreated MSW in Table 1. The treatment enhances the drying performance of MSW and thus the moisture content of the treated MSW reduced down to 11.6% from 33% in 48 h. This is due to the fact that the bound water in the cells of MSW became free water by destroying the cells under the hydrolysis reaction with steam during the treatment. This improvement in the drying performance leads to a lower energy consumption for removing moisture from MSW. There is a significant increase in the shelf life of the treated MSW due to the removal of bacteria, micro organisms and fungi by the action of high temperature steam. Also this treatment increases the density of the treated MSW, to almost four times compared with the untreated MSW. Further, this treatment makes MSW into uniform grounded powder so that it can be easily blended with coal. Interestingly, in addition to the size reduction of MSW, the hydro thermal treatment also removes bad odor, which helps to solve the problem related to handling of MSW.

2.3. Thermogravimetric analysis (TGA)

The combustion characteristics of Indian coal (IC), Indonesian coal (INC), Australian coal (AC), hydrothermally treated municipal solid waste (MSW) and their blends were studied using a simultaneous TGA/DTA analyser (SHIMAZDU D 50). The series of blends containing 10%, 20%, 30% and 50% of MSW on the weight basis

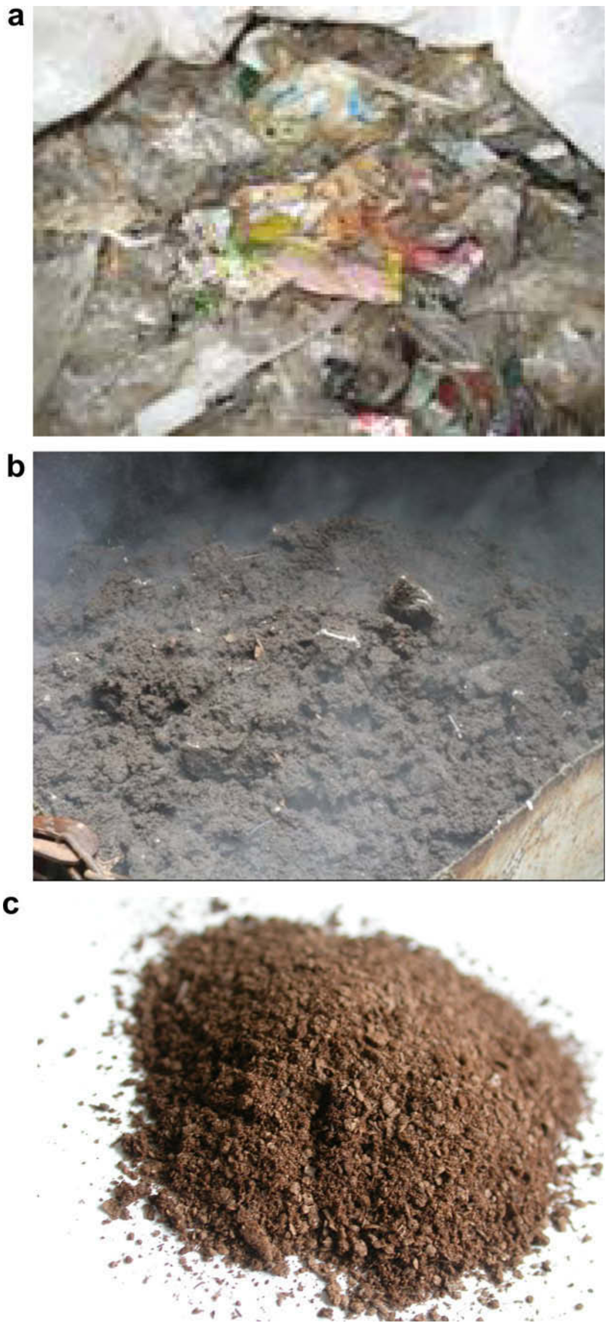

Fig. 2. Drying and crushing performance of the hydrothermal treatment. (a) MSW – before treatment. (b) MSW – after treatment. (c) Treated MSW – after natural drying.

were prepared with their particle size less than 180 μm (about 80 mesh). TG, DTG (first derivative of TG curve) and differential thermal analysis (DTA) analyses were done for obtaining weight loss profiles as functions of temperature and time. Differential thermal analysis (DTA) provides qualitative information about the energy associated with the process. This was done by heating the sample at a constant rate of 10 °C/min from the ambient temperature to 700 °C using a non-isothermal type of TGA. These dynamic runs were carried out by placing about 10 mg of dried sample on a pan. An oxidizing and an inert atmosphere were established during temperature-programmed combustion and pyrolysis by supplying a continuous flow of air and nitrogen (150 ml/min).

The TG and DTG profiles were analysed to find the characteristics parameters. After an initial moisture removal, the temperature at which the weight loss started was denoted as the volatile release temperature (T_v). Temperature at which the DTG curve showed peak value was denoted as the maximum weight loss temperature (T_m). The burnout temperature (T_f) was detected based on the mass stabilization. The ignition temperature (T_o) was decided based on the temperature at which the DTG had its peak value and the corresponding slope to the intersection with respect to the TG profile [10,14].

Table 3
Fuel analysis.

	Indian coal	Indonesian coal	Australian coal	Treated MSW[d]
Proximate analysis				
Moisture[a] (%)	12	11.97	3.4	11.6
Volatile matter[b] (%)	25.4	50.16	29.5	70.94
Fixed carbon[b] (%)	29	48.16	62.5	6.3
Ash[b] (%)	45.6	1.66	7.9	22.75
Volatile matter[c] (%)	46.69	51.01	32.03	91.83
Fixed carbon[c] (%)	53.31	48.97	67.86	8.155
Fuel ratio	1.14	0.96	2.12	0.09
Ultimate analysis[b]				
Carbon (%)	39.14	66.44	72.36	39.92
Hydrogen (%)	2.93	4.73	4.38	5.53
Nitrogen (%)	0.895	0.965	1.28	0.84
Oxygen by difference (%)	3.07	12.9	9.55	26.68
Calorific value[b]				
HHV (MJ/kg)	17.88	30.03	33	17.84

HHV-high heat value.
[a] As received basis.
[b] Dry basis.
[c] Dry ash free basis.
[d] Hydrothermally treated MSW, dried naturally for 48 h.

The properties of the Indian coal, Indonesian coal, Australian coal and the treated MSW were summarized in Table 3. For the ultimate analysis of these fuels, PerkinElmer made 2400 Series II CHN organic elemental analyser was used. In comparison with pulverized coal, MSW generally has higher volatile content but lower bulk density and net calorific value. The calorific values of the Indian coal and the treated MSW are almost the same and at around 17–18 MJ/kg, dry basis. So this can avoid the fear of variation in heat liberation due to uneven blending of MSW with coal. The Indonesian coal and the Australian coal hold very high energy content (30 MJ/kg, dry basis) which is the main contributor in deciding the amount of blending. Hence the Indonesian and Australian coals contain almost the double energy content compared with the treated MSW and the Indian coal. Further, the volatile contents of the Indian and Australian coals are much lower compared with the treated MSW, which are the key elements to initiate ignition. The treated MSW contains high oxygen content compared with coals. This is significant because the more oxygen a fuel contains, the easier it is to start to burn, or to achieve its ignition. So it is expected that the blending of high oxygen volatile content MSW with coal always results in ignition enhancement, i.e. an early ignition of coal before reaching high enough temperature where it is expected to ignite. This is one of the main technical barriers for implementation of co-combustion projects. Also this study aims to find how the parameters like HHV, volatile and ash contents influence the ignition characteristics.

3. Results and discussion

3.1. Pyrolysis behavior

Fig. 3 shows the pyrolysis characteristics of the Indian, Indonesian and Australian coals with various levels of MSW blends. The temperature at which the volatile starts to be released (T_v) is

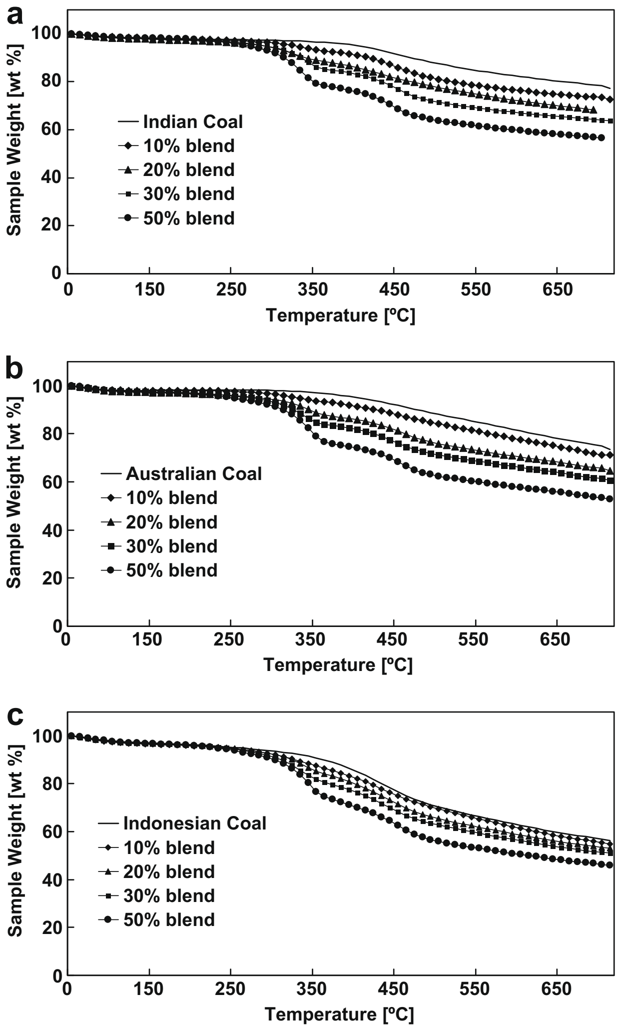

Fig. 3. Pyrolysis profiles for coal and MSW blends. (a) Indian coal blend. (b) Australian coal blend. (c) Indonesian coal blend.

decreasing with the addition of MSW. There was a clear improvement in the devolatization characteristics of the blend fuel with the addition of MSW. The rate of volatile release was proportional to the MSW blending proportion. So MSW blending helped to improve the devolatization phenomena of coals. This is due to the fact that the volatile content of MSW is released in lower temperature compared to coals. So in all these three coals, the volatile of MSW is released first. It can be seen clearly that the pyrolysis profile for the Indonesian coal does not change significantly by changing the blending ratio of MSW and differs from the ones of the Indian and Australian coals (see Fig. 3a–c). This is due to the fact that high volatile Indonesian coal releases it's volatile at lower temperature as MSW does, which leads to little weight loss difference in the pyrolysis profile among their blends. This difference of the liberation of the volatile from blend fuels at the same time should create a different kind of ignition effect. So the pyrolysis process alone is not enough to identify this effect. In the case of the Indian and Australian coals, the MSW releases its volatile very early compared to the coal volatile which leads to more significant weight loss difference among their blends. Also in particular, MSW contains large amount of volatile matter which are easy to ignite. In general, this kind of early release of the volatile from the fuel helps to improve the ignition performance. At the same time, there is a risk of the fuel getting ignited before the place where it is expected to burn, causing a fire hazard – the problem associated with the practice of blending. Hence only from the pyrolysis experiment the effect of the MSW blending on the ignition characteristics of coal cannot be verified, so a combustion study is very much required to ascertain this effect.

3.2. Combustion behavior

The burning characteristics of the Indian, Indonesian, Australian coals, MSW and their various blends have been studied using the TG profile as shown in Fig. 4. With the rise of the temperature, after a release of moisture, combustion of samples took place with associated weight losses. For the blends, quicker weight losses were observed, mainly due to early emission of volatile matter, which differentiates burning behavior of MSW compared with coal. The combustion of coal is mainly due to the combustion of the fixed carbon whereas in the case of MSW, this was dominated by combustion of the volatile matters, obviously due to their high volatile content. The characteristic parameters were obtained from the burning profile as shown in Table 4.

3.2.1. Effect of blending of MSW with different volatile content coals

The volatile matter content is very high for MSW compared with coal. Higher the volatile matter content, easier the fuel gets ignited and completes its combustion. So fuels containing large amount of volatile matter are easy to ignite, but such fuels tend to burn quickly. High volatile fuels generally have lower heating values. So it is expected that the blending of high volatile MSW with coal always lowers the ignition temperature. That is of particular interest in the case of the Indian coal, which needs ignition enhancer due to its low volatile and high ash contents. The effect of mixing MSW with the Indian coal is shown in Fig. 4a. As expected, the ignition temperature is reducing with the addition of MSW (see Table 4). The highly reactive MSW volatile liberated at lower temperature helps to support the ignition of the Indian coal. It is evident that the mass loss started earlier, i.e. at lower temperature for the blend fuel due to lower volatile release temperature of MSW. So the volatile matter released from MSW is burned and releases enough energy to reduce the ignition temperature of coal. This effect is more prominent when more MSW is blended with coal. Hence the higher the blending ratio, the higher the volatile amount released from MSW becomes and the greater in the reduction of the coal ignition temperature becomes. The steep weight loss slopes of the TG profiles corresponding to the char combustion are reduced with the increase of the MSW blending ratio, which confirms the reduction in the ignition temperature. The ignition temperature of the Indian coal-MSW blend follows the weighted average and hence exhibits an additive behavior. So a higher MSW blending ratio with the Indian coal will result in a very low ignition temperature causing a potential fire hazard, and the fuel may get burned well ahead of a point where it is expected to burn. Hence when using MSW to blend with the Indian coal, as it reduces the ignition temperature, care must be taken to ensure that reduction in the ignition temperature should be within the allowable range for the presently available equipment.

The burning profile for the treated MSW is also shown in Fig. 4a, for reference. The DTG profile of the treated MSW (see Fig. 4b) shows that there was a greater amount of weight loss rate in the low temperature region around 260 °C, this is due to the significant amount of weight loss by volatile release and combustion before char burning at 460 °C which differentiates the MSW combustion with the coal combustion.

Contrary to the Indian coal blend, the ignition phenomena of the Australian coal blend has shown a completely different trend as shown in Fig. 4c and Table 4. The ignition temperature of the Australian coal blend was not at all affected by MSW blending.

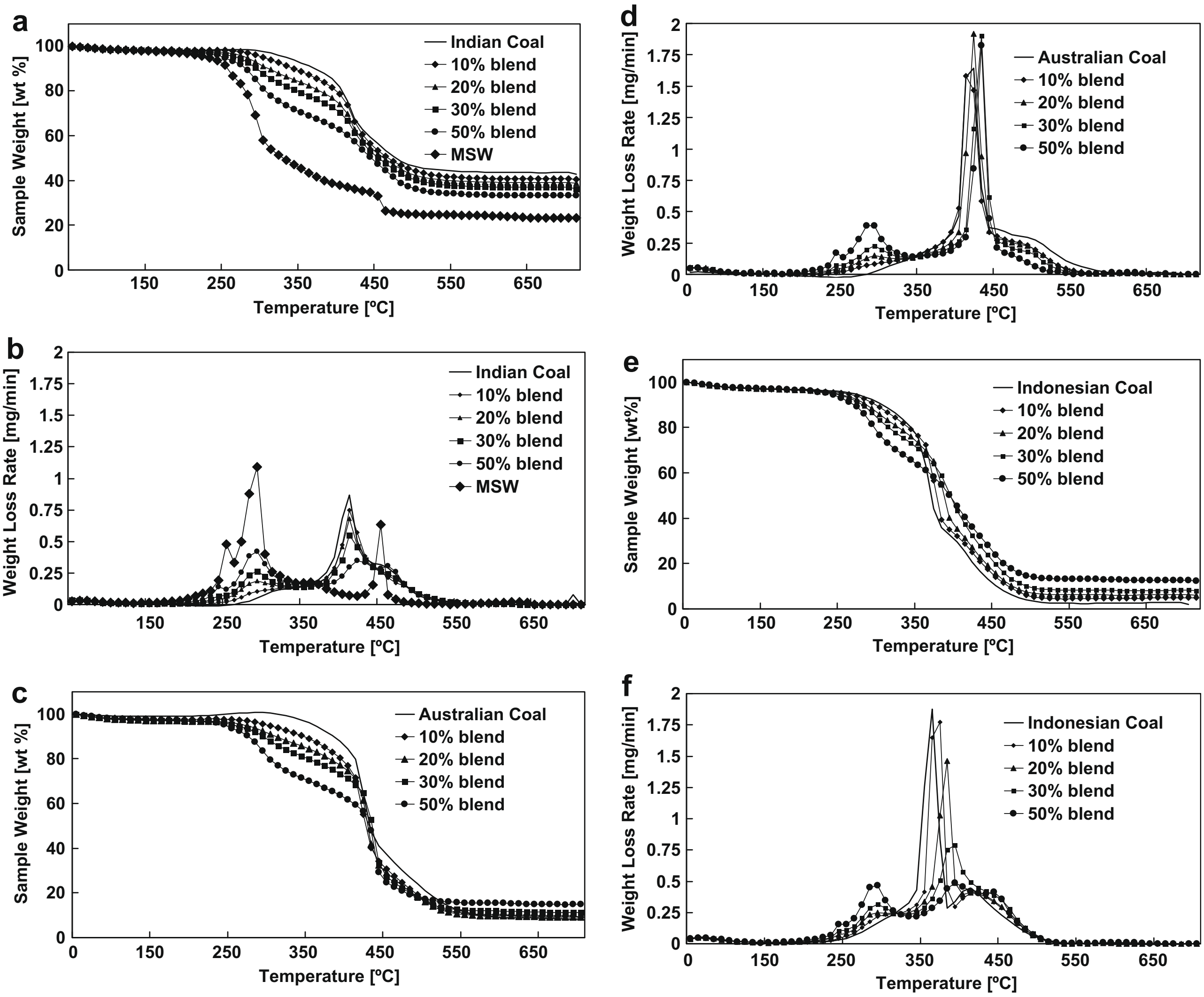

Fig. 4. TG and DTG profiles for coal and MSW blends. (a) TG profile for the Indian coal blend. (b) DTG profile for the Indian coal blend. (c) TG profile for the Australian coal blend. (d) DTG profile for the Australian coal blend. (e) TG profile for the Indonesian coal blend. (f) DTG profile for the Indonesian coal blend.

Table 4
Characteristic parameters of Indian coal, Indonesian coal, Australian coal, MSW and their blends obtained from burning profiles.

Sample	T_v (°C)	T_o (°C)	T_m (°C)	T_f (°C)	DTG max (mg/s)
IC	308	398	452	655	0.018
IC + 10% MSW	276	391	446	654	0.014
IC + 20% MSW	252	375	444	667	0.013
IC + 30% MSW	247	359	442	659	0.009
IC + 50% MSW	236	320	436	645	0.008
AC	325	416	471	681	0.036
AC + 10% MSW	289	418	481	662	0.037
AC + 20% MSW	263	411	478	668	0.043
AC + 30% MSW	246	418	478	678	0.043
AC + 50% MSW	240	417	473	655	0.046
INC	270	366	418	580	0.038
INC + 10% MSW	258	369	432	585	0.029
INC + 20% MSW	245	376	426	603	0.037
INC + 30% MSW	242	346	422	620	0.015
INC + 50% MSW	229	306	419	635	0.009
MSW	212	269	493	660	0.032

IC = Indian coal, AC = Australian coal, INC = Indonesian coal, MSW = municipal solid waste, T_v = onset temperature at volatile release and weight loss start, T_o = ignition temperature, T_m = temperature at maximum weight loss rate, T_f = burn out temperature detected as mass stabilization, and DTG max = maximum weight loss rate.

As a high rank coal, the Australian coal has very low volatile content and high amount of fixed carbon, which requires higher activation energy to initiate combustion. The coal char gets ignited only when it attains its own ignition temperature. An important difference of the MSW blending with the Australian coal compared with other coals was the increase in the maximum weight loss rate during the char burning (see Table 4). This is due to the synergic effect of burning of the MSW char along with the coal char at the same temperature resulting in a quick reduction in the weight. The char burning temperature for both the treated MSW and the Australian coal coincides at 460 °C. This shows an increase in the reactivity of the Australian coal with the addition of MSW. Hence a different behavior was seen for the Australian coal blend against the general perception of reduction in the ignition temperature with the addition of high volatile MSW. This is due to the fact that the energy supplied by the low energy content MSW volatile is not sufficient enough to reduce the ignition temperature. Fig. 4d shows the DTG profile of the Australian coal blend. It can be seen that the TG and DTG profiles of different level of blends coincides at the temperature around 450 °C. The slopes of these TG lines for the char combustion are the similar, which confirms the same ignition temperature for all the blends. Hence the MSW blending with the Australian coal did not produce any change in the ignition temperature. So the extent of acceptable blending is limited by the amount of energy content reduced by adding low energy content MSW.

The blending of the treated MSW with the Indonesian coal is of special interest due to their inconsistent behavior. Table 4 shows an increase in the ignition temperature of the blend up to 20% of MSW blending. The blend level of 30% and above exhibits a reduction in the ignition temperature. So a greater care is needed for utilizing the Indonesian coal blended with MSW due to its different nature of the ignition characteristics. There is an appreciable difference in the TG profiles of the MSW blended Indian, Indonesian and Australian coals. The TG profile for the Indonesian coal blend is given in Fig. 4e. For the blends of MSW up to 20%, the char combustion portion of the TG profile is shifted to a higher temperature with the same slope. In these blends, as shown in Fig. 4e, the nature of the volatile release is different and the TG curves are close to each other compared with the Indian and Australian coal blends shown in Fig. 4a and c. These figures show that the volatile release temperature of the Indonesian coal is lower than those of the Indian and Australian coals and hence the volatile releases of the Indonesian coal occurs along with the MSW volatile release. Hence the TG profiles for the Indonesian coal and its blends are very close to each other. The volatile release temperatures of the Indonesian coal and the treated MSW are 270 °C and 212 °C, respectively. Hence the addition of MSW with the Indonesian coal does not give much effect on the early release of the volatile. For a 10% of the MSW blend, the volatile release temperature reduces about 12 °C in the case of the Indonesian coal compared to a significant reduction of 32 °C and 36 °C (see Table 4) in the cases of the Indian and Australian coals. This phenomena of liberation of volatiles of both the treated MSW and the Indonesian coal at the same time, delays the ignition point due to dilution of the high energy coal volatile by the low energy MSW volatile. Beyond 30% of the MSW blends, the volatile released much earlier due to higher amount of the MSW volatile release and consequent burning leads to reduction in the ignition temperature resulted in changes in the slope of the TG curves. This explains the peculiar ignition characteristics of the MSW blends with the Indonesian coal.

3.2.2. Effect of blending of MSW with different HHV coals

From the heating value, the samples can be divided into two groups. Indian coal and the treated MSW have similar energy content of around 17 MJ/kg compared with higher energy content of around 30 MJ/kg for the Australian and Indonesian coals. For the Indian coal and MSW blend, change in the energy output due to blending is not expected for a given amount of fuel. But in the case of blending of low quality MSW with high quality fuels like the Australian and Indonesian coals, the energy content reduction associated with blending should be compensated by the increase of the amount of fuel to be burned.

Fig. 5a–c shows DTA profiles corresponding to the combustion of different rank coals and MSW blends. As shown in Fig. 5a, the DTA analysis for the Indian coal blend with MSW, the heat release exothermic curve shows two peaks, for volatile and carbon combustion, respectively. It can be seen that the first peak corresponding to the volatile combustion is moving towards left, i.e. to a lower temperature with the increase in the MSW blend ratio, which indicates an early release of the MSW volatile. Heat release pattern changes with the addition of MSW for the Indian coal. With an increase in the MSW blending ratio, the first peak corresponding to the volatile combustion increases while the second peak corresponding to the char combustion decreases. As shown in Fig. 4b, the reduction in the weight loss rate in the char combustion zone and consequent increase in the weight loss rate in the volatile combustion zone associated with the addition of MSW confirms with the above nature of the energy release. Hence in total, the amount

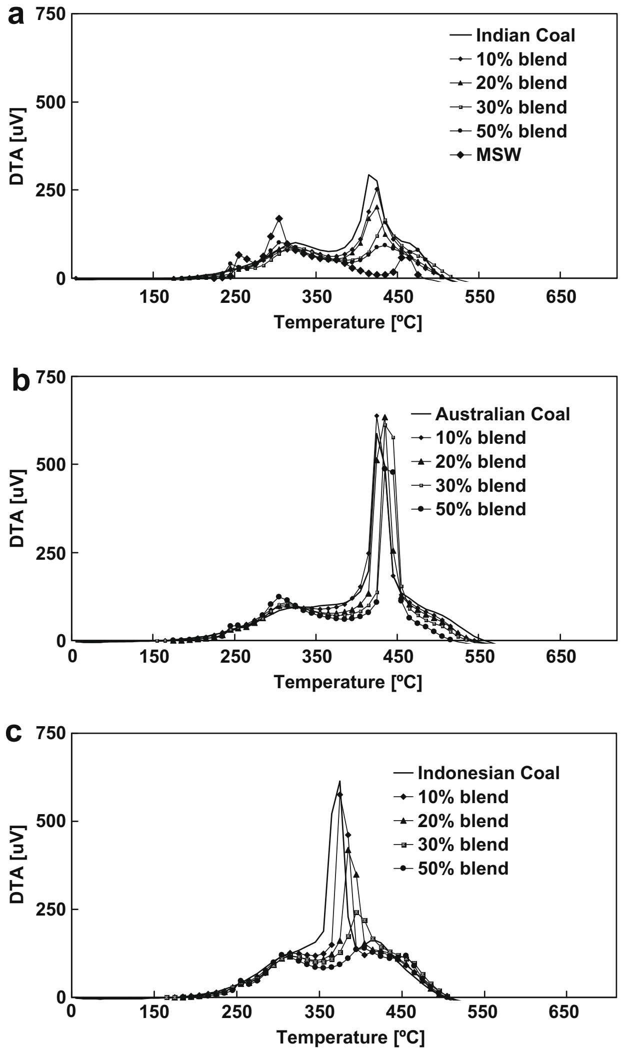

Fig. 5. DTA profiles for coal and MSW blends. (a) Indian coal blend. (b) Australian coal blend. (c) Indonesian coal blend.

of energy releases is not affected by the blending process except for the change in the pattern of the heat release. In the case of the Australian coal blends, the energy released by the volatile combustion is higher due to MSW blending, which can be clearly seen in an increase of the first peak of DTA analysis as shown in Fig. 5b. The nature and the temperature of the second peak corresponding to the char burning almost remained unaltered. Hence the effect of blending MSW with the Australian coal on the heat transfer pattern remained unchanged. But the area under the curve, which indicates the total energy output, is reducing with the increase in the MSW blending. This is due to the blending of lower heating value MSW with higher heating value coal. So for a given energy output, more amount of blend fuel is to be burned. This may demand an increase in the capacity for fuel feeding equipment and air handling equipment like fans. There is a significant increase in the weight loss rate in the volatile combustion zone due to blending of high volatile MSW as shown in Fig. 4d, for the DTG analysis. But these changes did not cause any reduction in the weight loss rate in the char combustion zone; instead it increases, basically due to burning of MSW char and coal char at the same time owing to their similar char burning temperature of around 450 °C.

For the Indonesian coal blend, the energy released by the early volatile combustion is hardly seen in Fig. 5c, as compared with other coals like the Indian and Australian coals shown in Fig. 5a and c. It is due to the fact that both the treated MSW (volatile matter = 70%) and the Indonesian coal (volatile matter = 50%) are high volatile fuels and substitution of the Indonesian coal by MSW does not affect much on the total volatile content, except for a reduction in the energy release by the volatile combustion. The increase in the weight loss rate in the volatile combustion zone as shown in Fig. 4f, did not produce any increase in the heat release as shown in Fig. 5c. For higher blends of MSW, there is an early burning of the MSW volatile alone, which leads to reduction in the ignition temperature. But it results in the reduction of the char weight loss rate. The reduction in the total heat released is apparent from the reduction in the area of the DTA curve. So similar to the Australian coal, more amount of blend fuel has to be burned for a given energy output due to blending of lower heating value MSW.

3.2.3. Effect of blending of MSW with different ash content coals

Ash is an inert material and does not participate in the combustion process; the left over ash content for various fuels and their blends were given in Table 5. The residual ash formed during the blend combustion depends on the individual blend components and linearly proportional to the blend ratio. No change in the amount of ash formation due to blending has observed. The amount of ash formed during co-combustion follows a linear function of the blend ratio. At any given blending ratio, the left over ash is the algebraic sum of the ash contents of the parent fuels.

3.3. Kinetic study

In order to confirm the kind of the weight reduction for the coal and its blends with MSW, Arrhenius kinetic parameters of the burning process were calculated for all samples as shown in Table 6. Regions 1 and 2 in Table 6 represent the activation energy values corresponding to the weight loss stages of volatile and char combustion, respectively. For combustion of coals the weight loss occurs in a single stage, i.e. for char combustion and thus single region of activation energy. In case of high volatile MSW, the combustion exhibits clearly two regions of weight loss, i.e. volatile and char and hence two regions of activation energy values. Similarly two region behaviors were observed for the Indian and Indonesian coals when blending more MSW, i.e. 30% and above. In general, the kinetic studies are carried out under the isothermal conditions. However, the use of non-isothermal conditions can be more useful if well defined conditions are selected for evaluating the kinetics. Such conditions can be obtained by heating the sample at a constant rate and using well controlled operating conditions in a thermogravimetric analyser [21]. A simple kinetic analysis was performed assuming the single step process, to verify the reactivity changes during the blend combustion.

3.3.1. Indian coal

It was evident from the table that the activation energy decreases with increasing the level of MSW blend ratio in the Indian coal. These results agree with those obtained by other author for woody biomass blending with coal [21]. This is because that the relatively weak bonds of MSW are less resistant to the heat and the more complex bonds of coal are more resistant to the heat. From the kinetic analysis it was found that for 10% and 20% blends, the reactivity is similar to that of coal. While there are two regions of the different reactivities in the case of 30% and 50% blends, the reactivity of the first region is close to that of the first region of MSW and the reactivity of the second region is close to that of the Indian coal. It was evident that for the blends of 30% and above, there was no interaction between MSW and coal burning.

3.3.2. Indonesian coal

Similar to the Indian coal the activation energy decreases with the increase of the MSW blend ratio with the Indonesian coal. Although a small blend of 10% MSW decreases the activation energy, 20% blend shows higher activation energy. This supports the behavior of the increase in the ignition temperate for the 20% blend. In this smaller blending ratio range, the addition of MSW delays the ignition of coal as described above. From the 30% blend and above, the activation energy keeps on decreasing with the increase in the blend level. But for the MSW blend of 30% and above, the blend fuel burns independently in two regions of burning as is the case of the Indian coal.

3.3.3. Australian coal

The activation energy values for the high grade Australian coal, which was dominated mainly by the high content of fixed carbon, behaves differently compared to other coals. Even though addition of MSW decreases the activation energy value initially, an increase in the activation energy value was observed with the addition of MSW more than 10% blend. Because of the high fixed carbon content in the Australian coal, the influence of MSW blending on the mass loss during burning is negligibly small even at 50% blend. This phenomenon causes the blended fuel to burn like a single fuel without any change in the ignition or maximum weight loss temperatures. In general, a fuel with low activation energy is usually

Table 5
Amount of ash produced.

Sample	Ash[a] (%)				
	In Fuel	In MSW blends			
		10%	20%	30%	50%
IC	45.6	41.2	40.3	37.3	33.3
AC	7.9	8.9	9.2	11.3	14.74
INC	1.66	3.7	6.6	8.5	12
MSW	22.75				

IC = Indian coal, AC = Australian coal, INC = Indonesian coal, MSW = municipal solid waste.
[a] Dry basis.

Table 6
Summary of kinetic parameters – activation energy.

Sample	Activation energy (kJ/mol)							
	Fuel (kJ/mol)		MSW blends (kJ/mol)					
	Region 1	Region 2	10%	20%	30%		50%	
					Region 1	Region 2	Region 1	Region 2
IC	119.3		110.2	96.5	78.7	92.7	83.2	101.7
AC	169.8		149.4	164.4	169.9		172.9	
INC	151.7		110.4	139	64	70	60.8	50.1
MSW	93.3	278						

IC = Indian coal, AC = Australian coal, INC = Indonesian coal, MSW = municipal solid waste.

considered to be easily ignited and combusted. But the activation energy values for the different level of MSW blends did not vary much, which shows the unlimited feasibility of MSW blending. So the limitation of blending MSW with the Australian coal comes mainly from the energy contents of the blended fuels rather than from the limitation of combustion.

3.3.4. Hydrothermally treated MSW

The combustion process for the treated MSW is mainly consists of the two stages. At the first stage, the volatile matter is combusted; and at the second stage, the fixed carbon is combusted. These results agree with those obtained by other authors for untreated MSW [22]. Hence two different regions of combustion resulted in two regions of activation energy values as shown in Table 6.

4. Conclusions

The co-combustion behavior of the hydrothermally treated MSW blends with the Indian, Indonesian, and Australian coals has been investigated using the TGA analysis. The conclusions drawn from the present study are summarized as follows:

- Blending of MSW with coal always improves the devolatization properties of coal.
- The pyrolysis and devolatization process provides little or no information on the effect of MSW blending with coal on co-combustion behavior. Therefore pyrolysis test is not sufficient to predict the co-combustion behavior.
- For the low quality coal such as high ash Indian coal, the addition of MSW enhances and supports the ignition of the coal which shows the feasibility of co-combustion.
- The early release of the volatile does not mean it always lowers the ignition temperature. Lowering the ignition temperature depends on the coal quality and energy released by the volatile. This effect is predominant with the low quality coal rather than higher grade coals.
- Blends ignition behavior cannot be predicted from the parent fuel properties only.
- Blends parameters other than ignition temperature show an intermediate behavior between coal and MSW, which may be predicted from the weighted sum of the blend components.

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